Tsukuba develops key role in Japan's research efforts

Dr Mohamed Henini

Tsukuba Science City is home to many of Japan's leading research institutes and is playing a key role in the country's development of low dimensional structures. Among the organizations doing important work in this area are the National Research Institute for Metals and the Institute of Materials Science at the University of Tsukuba.

Located about 60 km Northeast of Tokyo, Tsukuba Science City was designed to relieve overcrowding in the Tokyo area, as well as to provide a focus to respond to the nation's growing needs in science, technology and education. The Japanese government spent nearly ¥1.6 trillion between the time the Science City was approved in 1963 and its completion in 1980.

This investment has seen Tsukuba become home to both completely new facilities and some that have been moved from Tokyo and its suburbs. There is a special emphasis on educational organizations and national research institutes in Tsukuba with all types of multidisciplinary research, from basic to applied, undertaken with state-of-the-art equipment. In recent years, due to its efficient and organized facilities, the city has also attracted a number of private research organizations.

Tsukuba Science City is gaining recognition from around the world as an international research centre. There are more than 200 government, academic and private institutions employing in excess of 12 000 full-time researchers. As Japan strives to maintain its status in science and technology, Tsukuba seems certain to serve as the focus for an increasing number of global research projects, and to make a major contribution to the field of international science.

The research and academic institutions whose fields are related to low dimensional structures include the National Research Institute for Metals (NRIM), the University of Tsukuba, National Institute of Advanced Interdisciplinary Research (NAIR), and Electrotechnical Laboratory (ETL), the largest national research laboratory in Japan. This article will look at some of the activities being undertaken at the first two of these organizations.

NRIM's broad focus

The research activities at NRIM are concentrated on developing innovative materials to provide the basis for advanced technologies. There are several divisions whose research includes work on superconducting materials, intermetallic compounds, multi-functional and intelligent materials, and structured materials. Research on material properties under extreme environments, such as high magnetic fields at ultra high or low temperatures, and high vacuum fields is also undertaken at NRIM. The total research budget for the 1998 fiscal year was an astonishing ¥12 032 855 000, while the total personnel exceeded 400.

The Physical Properties Division of NRIM, headed by Prof. G.Kido, is mainly interested in the electronic properties of advanced materials. The main topics under investigation include a new magnetic phase in low dimensional magnetic materials, the quantum Hall effect in 2D semiconductors, quantum phenomena in organic materials, and magneto-optical properties in semi-magnetic semiconductors. Various kinds of single crystals have been grown using different techniques such as tetra-arc furnace, tungsten mesh-heater furnace, electron beam furnace, and electron beam crucible welder.

Recently there has been considerable interest in semiconductor quantum dots (QDs) due to their interesting physical properties and potential applications in advanced semiconductor lasers. Several methods have been used for the fabrication of these quantum structures including electron beam lithography and self-organizational growth. The latter technique is based on the Stranski-Krastanov growth mode caused by the lattice mismatch between the substrate and the epitaxial layer. However, it has been very difficult to fabricate QDs on a nearly or exactly lattice-matched layer such as GaAs/AlGaAs.

N.Koguchi and his co-researchers at NRIM have proposed a new technique called droplet epitaxy. This process starts with the formation of numerous III-element droplets, such Ga or InGa, with homogenous sizes of around 10 nm on the surface. Then an impinging As molecular beam reacts

0961-1290/99/$ - see front matter

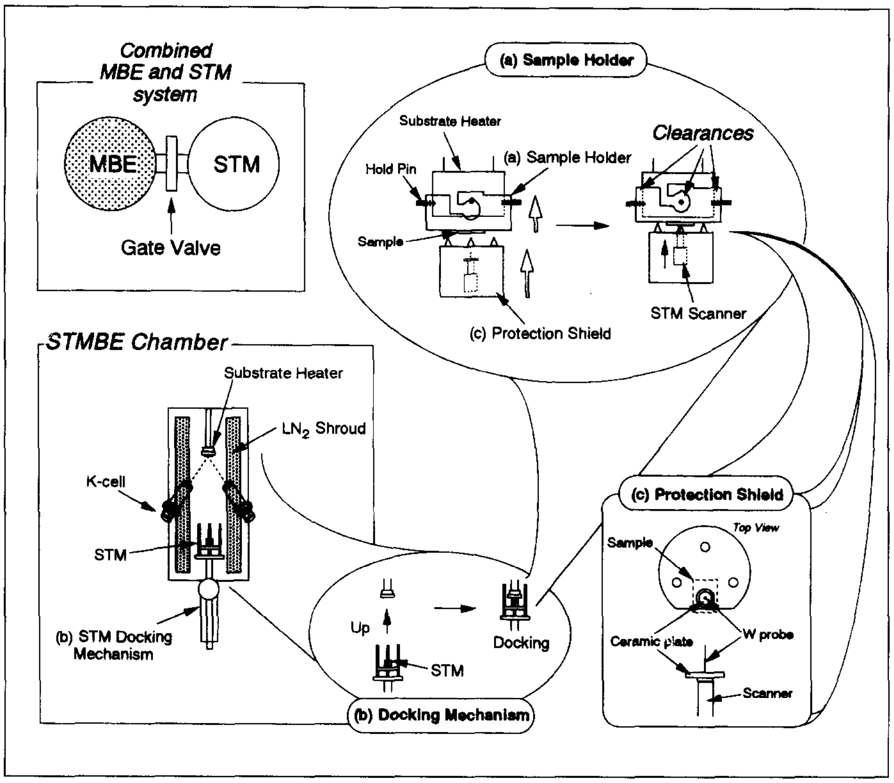

Figure 1. A comparison of the standard combination of STM and MBE with the novel STMBE system. The STMBE system has (a) a novel sample holder, (b) a STM docking mechanism and (c) a special shield, which protects the STM apparatus from material depositions and radiation. (Courtesy of Dr S.Tsukamoto.)

with the droplets to form GaAs or InGaAs epitaxial microcrystals. QDs have been fabricated by this technique in the GaAs/AlGaAs and InGaAs/GaAs materials systems. The size and distribution of QDs correspond to those of metal droplets, and can be controlled by means of substrate temperature and/or the molecular beam intensity of the metal atoms. The developers believe the technique is promising for the fabrication of compound semiconductor QDs not only for lattice-matched systems, but also for the lattice-mismatched systems.

NRIM's advanced combination

Molecular beam epitaxy (MBE) and scanning tunnelling microscopy (STM) have established themselves as a very powerful combination for the observation of real-space semiconductor surfaces, especially for (100) GaAs, where extremely high lateral and vertical resolution can be obtained. Now, S.Tsukamoto and his co-workers at NRIM have designed a new system, called scanning tunnelling molecular beam epitaxy (STMBE), in which STM and MBE are completely one.

Several problems were successfully overcome in order to achieve STMBE operation, such as the need to create a vibration- and noise-free environment for STM observation. For example, to overcome the noise problems associated with a conventional MBE system, such as liquid nitrogen bubbling, vacuum pumps, and radiation noises from material sources, the NRIM team has designed a novel sample holder with wide clearances around hold pins, and a novel STM docking mechanism (Figure 1). The STM unit is protected from material depositions and radiation from substrate and source heaters by a special shield (Figure 1c).

Using this STMBE system NRIM researchers have successfully observed Ga adatoms on GaAs (001) (2x4)-As surface during MBE growth. It was found that Ga adatoms are self-organized about one unit cell distant from the B-step edge and on a missing dimer row - the theoretical predictions agree well with these experimental findings. In addition, three Ga

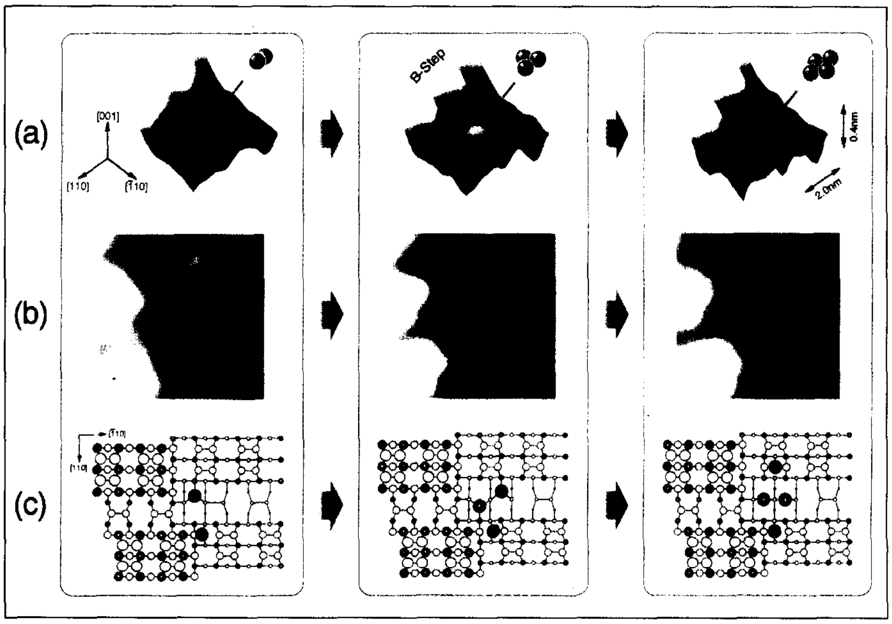

Figure 2. (a) Three-dimensional and (b) plane-view filled-state STM images of Ga adatoms at 25 s (left), 250 s (centre), and 500 s (right) after the supply of 0.1 monolayer of Ga at 200°C. (c) Shows a model of this self-organizing process of Ga adatoms. Ga and As atoms are indicated by filled and unfilled circles, respectively. (Courtesy of Dr S.Tsukamoto.)

atoms formed a trigonal surface structure, which changed to a tetragonal structure when one Ga atom was added. This is illustrated in Figure 2, which shows the three-dimensional, and plan-view filled-state STM images of Ga adatoms near the B-type stepped terrace observed after 25 s, 250 s and 500 s after the supply of Ga. The conclusion is that the surface reconstruction strongly affects the self-organization process of Ga adatoms. Figure 2(c) shows a model of this self-organizing process of Ga adatoms.

QDs at University of Tsukuba

Developing the technology for the high-density integration of QDs is one of the most important objectives currently being pursued in single electron devices and low-dimensional physics. The formation of high-density QDs by self-organization is one of the most promising techniques to meet this goal. The growth conditions, as such growth rate, growth temperature and film thickness, can be used to control the size of the QDs. The control of the density and ordering of these self-assembled QDs, however, is a crucial issue to be resolved. In addition, the electronic coupling between QDs is also important for further development of low-dimensional devices and physics.

Prof. H.Koyama and his co-workers at the Institute of Materials Science at the University of Tsukuba have shown that well-ordered InGaAs QDs can be fabricated on (311)B GaAs substrates by using atomic hydrogen-assisted MBE. In their experiment the (311)B GaAs substrates were cleaned with atomic hydrogen at 500°C. A GaAs buffer layer of 300 nm was then deposited at 580°C. This was followed by the growth of $In_{0.4}Ga_{0.6}As$ QDs at various growth temperatures ranging from 460 to 540°C. The surface morphology and size and position of

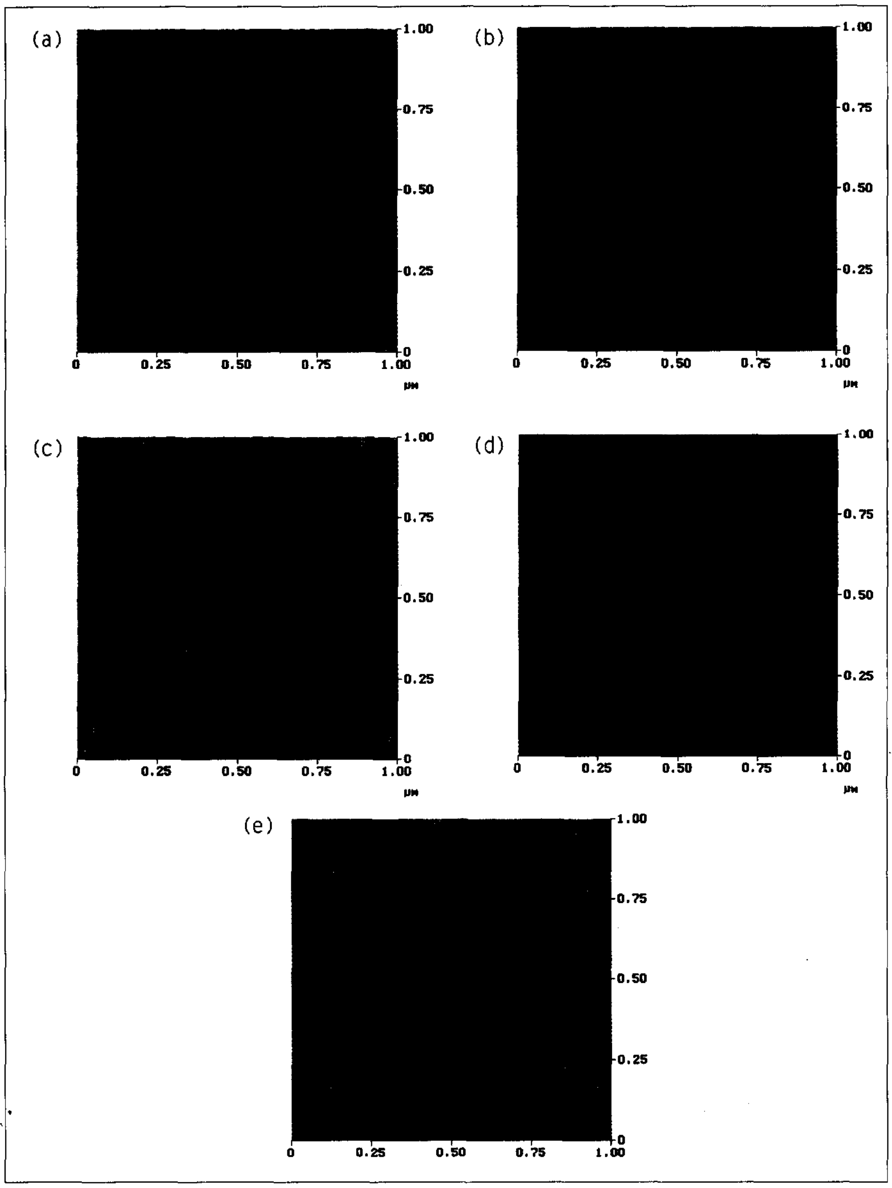

Figure 3. AFM images of $In_{0.4}Ga_{0.6}As$ QDs grown on (311)B GaAs substrates at a growth temperature of (a) 460°C, (b) 480°C, (c) 500°C, (d) 520°C, (e) 540°C. The nominal thickness of $In_{0.4}Ga_{0.6}As$ was 8.8 monolayers (ML), 7.7 ML, 8.8 ML, 12.7 ML, and 15.5 ML, respectively. (Courtesy of Prof. H.Koyama.)

the QDs were analysed by AFM. The dependence of the size and density of the QDs on the growth temperature are shown in Figures 3a-3e. It was found that the QD diameter decreased from 120 nm at 540°C to 20 nm at 460°C while the density increased from 5.6×10^9 cm^{-2} to 1.4×10^{11} cm^{-2} with a deterioration of the ordering. As can be seen from Figure 3 the QDs become highly packed with decreasing growth temperature. In particular the surface coverage of QDs is almost 100% for the growth temperatures of 460 and 480°C. It is worth noting that the QDs do not appear to coalesce to form large islands as observed in the conventional Stranski-Krastanov mode of QD growth.

The effect of stacking on the dot formation mode was also studied. Figure 4 shows plan-view transmission electron microscopy (TEM) images of a single layer and stacked $In_{0.4}Ga_{0.6}As$ QDs grown at 460°C. The three-stacked QD layer sample has 5 nm GaAs spacer layers and was capped with a 15 nm

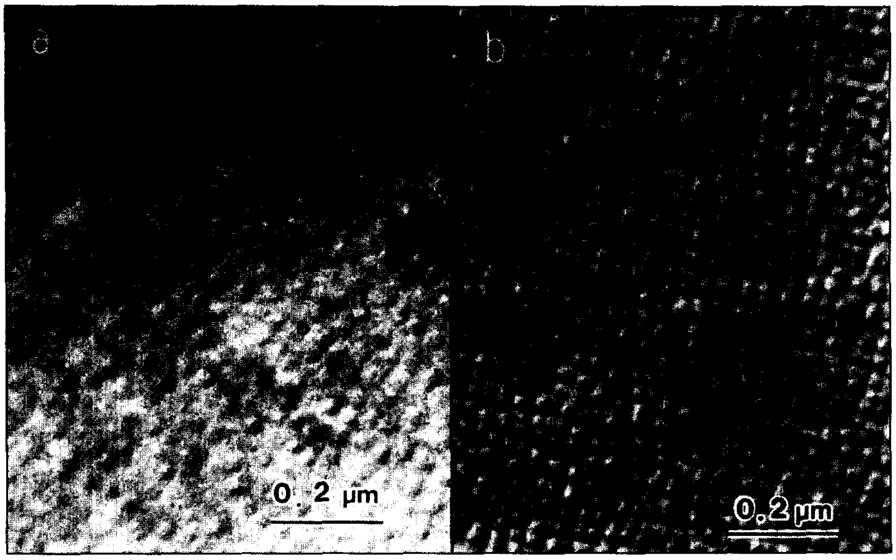

Figure 4. Plan-view TEM of (a) a single layer of $In_{0.4}Ga_{0.6}As$ QDs and (b) three stacked $In_{0.4}Ga_{0.6}As$ QDs. (Courtesy of Prof. H.Koyama.)

GaAs layer. The QDs are clearly resolved in the stacked sample indicating that the QDs are aligned along the direction of growth, and that a non-coalesced structure is maintained in each InGaAs layer.

Conclusion

Japan is promoting various challenging research programmes to explore the nature of atomic-scale structures, which are expected to play a major role in future electronics applications. To realize a creative environment where major efforts can be focused for achieving these goals, Japan has implemented a joint research scheme involving industrial, academic and government sectors, which allow intensive investment and gathering of excellent human resources.

Acknowledgements

I would like to express my sincere thanks to Prof. G.Kido who made my visit to NRIM very enjoyable and scientifically rewarding.

Contact: Dr Mohamed Henini
School of Physics and Astronomy
University of Nottingham
Nottingham NG7 2RD
UK.
Tel: +44 (0)115 9515195.
Fax: +44 (0)115 9515180.
E-mail: mohamed.henini@nottingham.ac.uk.